J. Wind Eng. Ind. Aerodyn. 97 (2009) 439–454

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

# Numerical simulation of atmospheric boundary layer flow over isolated and vegetated hills using RAMS

Leanderson M.S. Paiva [a], Gustavo C.R. Bodstein [b,*], Wallace F. Menezes [c]

[a] Federal Center of Technological Education Celso Suckow da Fonseca (CEFET/RJ), Av. Maracanã, no. 229, Bloco A, Torre – Maracanã, 20271-110 Rio de Janeiro, RJ, Brazil
[b] Department of Mechanical Engineering – Poli/COPPE, Federal University of Rio de Janeiro (UFRJ), Centro de Tecnologia, Bloco G, sala 204 – Ilha do Fundão, 21945-970 Rio de Janeiro, RJ, Brazil
[c] Department of Meteorology – IGEO, Federal University of Rio de Janeiro (UFRJ), CCMN, Bloco G – Ilha do Fundão, 21941-590 Rio de Janeiro, RJ, Brazil

ARTICLE INFO

*Article history:*
Received 10 July 2007
Received in revised form
12 February 2009
Accepted 2 July 2009
Available online 12 August 2009

*Keywords:*
Atmospheric boundary layer
Flow over hills
RAMS
Neutral and non-neutral atmosphere
Numerical simulation
Environmental flows
Wind energy

ABSTRACT

Atmospheric boundary layer flows over hills are important in the analysis of wind energy systems, dispersion of pollutants in the atmosphere and many meteorological and engineering applications. The objective of this work is to use the Regional Atmospheric Modeling System (RAMS), a numerical mesoscale model generally used for weather forecast and atmospheric case studies, to simulate the flow over isolated hills, covered with vegetation of uniform and non-uniform roughness length. The ability of the model to simulate this type of flows is tested by comparison with actual microscale data. The flow is assumed to be two-dimensional and quasi-steady, and the atmosphere is dry under statically neutral and non-neutral stability conditions. The numerical grid covers a large physical domain, with constant mesh spacing in the horizontal direction and a telescopic mesh in the vertical direction. All cases studied show that the domain size, the boundary conditions and the turbulence models play an important role in the simulations. The numerical results indicate that the Mellor and Yamada turbulence model performs better than the Smagorinsky model. When compared to the Askervein, Black Mountain, Cooper's Ridge field data and other numerical and analytical results from the literature, the RAMS results predict reasonably well the vertical profiles of the mean velocity and of the absolute and relative speedups.



## 1. Introduction

The length scales corresponding to the various obstacles built on the Earth's surface either by nature or by man covers a wide range, going from small houses to tall apartment building or shopping malls, or from small isolated hills to complex mountain chains. In particular, hills are responsible for changes in the local wind regime with respect to the upstream logarithmic wind profile that develops on a flat terrain far upstream of the hill—the reference site (RS). In general, there is an increase of the wind speed near the hilltop (HT) and a reduction of the wind speed on the upwind and downwind slopes near the ground surface.

The study of the flow over hills in the atmospheric boundary layer (ABL) has been of interest since the 1920s, when glider pilots discovered the presence of strong vertical updrafts in the region close to hilltops and used these updrafts to reach high altitudes. The flow over hills is also extremely important to meteorologists, engineers, sportsmen, and the military, among others. The military is interested in ABL flows over hills during air operations that require equipment and troops to disembark using parachutes, when the horizontal wind next to the ground becomes important. Similarly, sports activities, such as glider and balloon flights, rappel, rock climbing and skiing, also benefit from the detailed knowledge of the wind speed over hills and mountains.

Meteorologists are interested in the ABL flow over hills during the development and validation of numerical codes that are accurate for weather and climate forecast. These codes are strongly dependent on the boundary conditions and on the physical and mathematical models adopted for the ABL. Taylor and Lee (1984) cite other meteorological applications, such as dispersion of pollutants in the atmosphere, pesticide applications on plantations and forests, and ground erosion caused by local winds.

On the other hand, the distribution of the mean wind velocity in the ABL next to the surface is essential for engineering applications. The effect of the topography as an amplifying factor of the wind speed in the ABL is key to wind energy studies, since the development of wind atlases based on the wind speed distribution in the ABL is the first step in the assessment of the wind energy potential of a region (Troen and Petersen, 1989).

* Corresponding author. Tel.: +55 21 2562 8406; fax: +55 21 2562 8383.
*E-mail addresses:* leanderson@cefet-rj.br (L.M.S. Paiva).
gustavo@mecanica.coppe.ufrj.br, gbodstein@yahoo.com (G.C.R. Bodstein).
wallace.menezes@gmail.com (W.F. Menezes).

0167-6105/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jweia.2009.07.006

Additionally, the careful site selection to efficiently install wind turbines requires detailed knowledge of the wind profile over hills (Barnard, 1991). Because the output power of a wind turbine is proportional to the cube of the wind speed, a small wind speedup corresponds to a very large power increase (Troen and Petersen, 1989). Engineers also need to know the height of the maximum speedup to calculate the wind loads on structures that are located on the hilltop, such as antennas and power transmission towers. The characteristics of the aerodynamics of buildings (Lalas and Ratto, 1996) on the top of hilly areas also require the knowledge of the wind distribution in the ABL because the loads resulting from the pressure and shear stress distributions are proportional to the square of the wind speed. Hence, small variation in the wind speed produces large load variations. The assessment of the environmental impact due to man-constructed obstacles in mountain regions also needs the knowledge of the modifications to the ABL airflow induced by topographic features.

The calculation of the ABL flow over hills in practical applications is a difficult task to perform. Field experimental campaigns are extremely expensive to be carried out every time a real problem needs to be solved, whereas wind tunnel experiments do not always incorporate all the physics involved. Analytical studies are limited by the inherent difficulties to treat real hill geometries and boundary conditions and they are also limited by the complexity of the model equations that try to mimic the most important physical phenomena present in the ABL. A more feasible procedure is to use numerical models to analyze the problem. One of the first theoretical studies concerning the flow over hills is due to Queney (1948), who discusses the influence of the topography on some of the physical quantities of the flow. However, the first detailed study related to the flow over isolated low-sloped hills is due to Jackson and Hunt (1975), who developed an analytical linear theory based on asymptotic expansions to divide the flow in two regions, an inner region dominated by shear stress perturbations and an outer region dominated by pressure perturbations, under statically neutral atmosphere. Jackson and Hunt's work have become the basis of other subsequent analytical theories, such as the ones developed by Taylor and Lee (1984), Hunt et al. (1988a, 1988b), Lemelin et al. (1988), Finnigan (1992), and Pellegrini and Bodstein (2005).

Simultaneously to the development of analytical theories, numerous field experiments have been made to better understand the flow over hills. Taylor et al. (1987) provide an excellent review of some of the most significant studies. Wind tunnel experiments, such as the ones of Britter et al. (1981) and Teunissen et al. (1987), have also been performed to characterize the main physical effects that occur in the ABL flow due to the presence of hills.

The detailed physical behavior of the flow over hills has been investigated in many numerical studies that simulate the entire ABL flow in the neighborhood of the hill. Before Jackson and Hunt (1975), some attempts to solve the problem numerically have been done by Alexander and Coles (1971), Frost et al. (1973) and Gal-Chen and Sommerville (1975). The complexity in the theory of Jackson and Hunt (1975) has motivated the appearance of the numerical models developed by Taylor (1977) and Bouwmeester (1978), that include non-linear terms, those devised by Walmsley et al. (1982) and Taylor et al. (1983) for fully developed flows, the MSFD (Walmsley et al. 1982) and the MS3DJH (Walmsley et al. 1986). The work of Walmsley and Taylor (1996) reviews extensively these linear models. Non-linear modeling avoids the original subdivision of the flow into regions through the use of a finite difference mesh (Taylor, 1977; Deaves, 1980). Sykes (1980) and Newley (1985) present other interesting modeling results for non-linear equations obtained in the 1980s. Some of the finite difference models produced by Beljaars et al. (1987) and Zeman and Jensen (1985) use again linearizing assumptions.

More sophisticated numerical models such as WASP (Troen et al., 1988), MS-Micro (Walmsley et al., 1990) and NLMSFD (Xu et al., 1994) have been created to predict the flow over isolated hills and also over complex terrain. Although these models have been developed specially for flow over hills, they incorporate simplifying assumptions that limit their accuracy for engineering applications. Recently, specific numerical models for the flow over the Askervein hill have been developed by Castro et al. (2003) and Undheim et al. (2006). Castro et al. (2003) use a terrain-following coordinate system and a two-equation ($k$–$\varepsilon$) turbulence model based on a finite volume discretization of the flow equations in primitive variables to study the importance of spatial discretization and the limitations of the turbulence model. They have observed that: the numerical results underestimate the relative speedup near the ground and at the hilltop; the flow's most prominent feature is the appearance of an intermittent recirculation region in the lee side of the hill; and the reduction in the characteristic roughness near the top of the hill is important to be taken into account in a numerical simulation. Undheim et al. (2006) uses the flow solver "3DWind" to explore numerically new aspects of the Askervein hill flow case, such as the flow sensitivity to the grid spacing, to the incident wind direction, and to the vertical resolution of the topographic data. Undheim et al. (2006) have found that the vertical resolution dependence is mainly attributed to the wall functions, the numerical results for the several wind directions tested in the simulations give less veering than found in the experiments, and the sensitivity to the vertical resolution of the topographical data is found to be high close to the ground at the hilltop, where the speedup is most important. All these conclusions highlight the importance of modeling correctly the non-linearity of the subgrid processes near the surface upon which large and mesoscale numerical models devised for weather and climate forecast are strongly dependent. The dynamics of the separation phenomena, the recirculating flow regions and the turbulent wake associated to flows over hills are key factors that must be studied in detail. Special care must be taken to choose the boundary conditions on the surface and on the lateral and upper boundaries of the domain.

The general objective of this work is to assess the ability of RAMS—Regional Atmospheric Modeling System (Walko et al., 1995), a numerical mesoscale model generally used for weather forecast and atmospheric case studies, to simulate numerically the wind in the ABL, in a microscale level. We assume the hill to be isolated, covered with uniform and non-uniform vegetation, and the flow to be two-dimensional and quasi-steady, in a statically dry atmosphere, under neutral and non-neutral stability conditions. For this purpose, we run version 3b of RAMS, resolving the simplified problem with very fine numerical grids, specific turbulence parameterizations and distinct boundary conditions. The specific objectives are twofold. Firstly, from a meteorological point of view, we aim at identifying how well RAMS, a mesoscale model, is able to predict the microscale features of the flow in the ABL from careful physical assumptions and unusually ultra-fine resolutions. Secondly, we desire to investigate the capability of RAMS to be used in specific non-meteorological applications, such as wind energy and other engineering applications. For these latter cases, we need to run the numerical model in very high resolution, so that the details of the wind speed distribution may be predicted accurately. That is one of the reasons why a two-dimensional model has been chosen, since three-dimensional models, run at these resolutions, may become too expensive. In particular, for wind energy and engineering applications, three-dimensional simulations require extremely high-resolution grids, which may prohibit any meaningful study to be carried out. Because of that, two-dimensional simulations can supply very useful information, such as the approximate location of flow